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ASD TECHNICAL REPORT 61-457

THE EFFECTS OF TRANSVERSE ACCELERATIONS AND EXPONENTIAL TIME-LAG CONSTANTS ON COMPENSATORY TRACKING PERFORMANCE

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SCHOOL OF MEDICINE
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AEROSPACE MEDICAL LABORATORY
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
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FOREWORD

This study was conducted under Contract AF 33(616) - 5407, Project 7222, "Biophysics of Flight", Task 71746, "Acceleration in Flight" with Dr. John P. Meehan serving as Responsible Investigator, and submitted by the author in partial fulfillment of the requirement for the degree Doctor of Philosophy at the University of Southern California. The author is presently at Defense Systems Division of General Motors Corporation, Warren, Michigan.

The author wishes to express his sincere gratitude to Professors Neil D. Warren, Floyd L. Ruch, and William W. Grings, Department of Psychology, for their encouragement, support, assistance, and advice while serving as members of the author's Qualifying and Dissertation Committees.

Grateful acknowledgments are extended to: Mr. William Silliman, North American Aviation, Inc., for serving as analog computer operator; Mr. Paul Tobias, Department of Physiology, for serving as centrifuge operator; Mr. William Monzon, Radio Corporation of America, for preparing the schematics and figures presented in this Dissertation; and the Management of North American Aviation, Inc., for providing the analog computer and technical personnel necessary for conducting this study.

Special acknowledgment is made to Mr. Carl Lafors, Electrical Engineer, for the engineering design and fabrication of the control system housing and associated equipment for this study, as well as excellent engineering support in other studies conducted by this author.

Finally, to Dr. John P. Meehan, Associate Professor of Physiology, whose technical assistance, administrative support, generosity, and understanding has made this study possible, the author offers his deepest thanks.

ABSTRACT

A study was conducted to determine the effects and interactions of front-to-back transverse accelerations, in the magnitudes of 0, 3 g, and 6 g, and exponential time-lag constants of 0.1, 1.0 and 2.0 seconds on human control performance on a compensatory tracking task.

In general, the results substantiated predictions of human tracking performance based on Helson's U-hypothesis and Principle of Generality. Concepts from information theory are introduced to explain certain learning phenomena which occurred in the course of the experiment.

PUBLICATION REVIEW

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I. INTRODUCTION

With recent and anticipated technical developments in the field of rocket propulsion, a great deal of consideration is being given to the many problems of successfully placing a human into orbit and returning him safely to the earth's surface. One of the problems encountered in the development of manned space vehicles is the evaluation of human control capabilities while exposed to relatively high-magnitude long-duration accelerations during the critical boost and re-entry phases of the mission. It is with this question that this study is concerned.

A. Time-Lags and Human Performance

The question of the effects of time-lags on human control performance has been treated in a large number of studies reported in the experimental literature. Of significant import are the types of time-lag, of which there are basically three: (1) transmission, (2) exponential, and (3) sigmoid.

Conklin (6) while discussing transmission lags, points out that following a control movement, a fixed time interval expires before information relative to the movement is visually displayed. Exponential lag, however, produces an exponential output of the control displacement and is defined as the time interval between the control input and 63% of the maximum output. The control movement, therefore, is immediately perceived but attains completion as an exponential function of time. It should be clear, then, that a transmission lag is a complete interruption, or loss, of visual information, whereas, exponential lag is only a partial loss. Based on classical learning theory (24), one would predict that performance would be better with exponential lag than with transmission lag (due to more immediate knowledge of results), with sigmoid lags falling somewhere between the two. This has not only been demonstrated experimentally, but, from a measurement point of view, error is generally measured as a function of time so that while the operator is waiting for the response from the transmission lag, error will, of course, be accrued.

According to Senders (28) and Ely, Bowen, and Orlansky (7), exponential and sigmoid lags may either improve or degrade performance, depending on interactions with other parts of the machine dynamics. Levine (20) and Conklin (6), on the one hand, report that when the gain is optimally set, the addition of an exponential lag between the operator's control output and the machine output will degrade performance. Levine (20) used delays up to 2.7 seconds, whereas, Conklin (6) used delays up to 16 seconds. Rockway (27), on the other hand, reported that if the gain were too high causing continual overshooting, the addition of a lag would serve to reduce the output amplitude and, thereby, improve performance. Ely, Bowen, and Orlansky (7) also point out that transmission lags normally degrade performance even though the lags may be so small that the operator is unaware of them.

In terms of principles of skilled performance Helson (14), based on his own research with various types and parameters of control systems, has formulated five principles of "optimal human operation". Two of these are particularly relevant: (1) the U-hypothesis, and (2) the principle of generality or transfer of the optimal.

With regard to the U-hypothesis, Helson (14) states that human performance will tend to be optimal as judged by accuracy, efficiency, and comfort, over a more or less broad band of values for a given stimulus-variable outside of which it becomes noticeably poorer. When performance is plotted in terms of error or the reciprocal of accuracy, the resultant curve is roughly U-shaped. Within the minimal band performance is less affected by changes in the variable than on either side. The U-hypothesis expresses the fact that organisms can adapt to a fairly wide range of stimulus values and function optimally in this range.

With regard to the Principle of Generality, Helson (14) states that stimulus-values in the optimal band tend to stay optimal when accessory conditions are changed.

There have been a number of recent experiments reported which support Helson's principles. Chernikoff and Taylor (5) studied the effects of course frequency and aided time constants of 0, 0.5, and ∞ on pursuit and compensatory tracking. A U-shaped function was found for both cases with the optimal aided time constant being 0.5 second. It should be noted that the authors did not identify the U-function as such. Pearl, Simon, and Smith (25), Hartman (13) and Garvey and Henson (11) have also obtained experimental results which, although demonstrating the U-hypothesis and the principle of generality, did not mention these specifically as supporting Helson's principles.

B. <u>Human Performance Under Acceleration</u>

There have been a very large number of studies reported in the literature concerning the effects of physical forces on human tolerance and performance. In the interests of brevity, the reader is referred to an excellent summary article by Brown and Lechner (3).

Of particular relevance to this study are the results of Bryan (4), Kaehler and Meehan (19) who reported a <u>differential effect</u>, in that psychomotor motions in a direct opposition to the direction of the acceleration vector requires longer time intervals than those activities which require motions perpendicular to the direction of the acceleration vector.

Other performance studies of relevance are those of Preston-Thomas, et al. (26), Kaehler (18) and Brown and Collins (2), who report that, in general, human performance in a continuous control task is degraded as a function of increased acceleration.

C. Experimental Hypotheses

The experimental hypotheses which were to be tested in this study, stated at the general level, are as follows:

1. Compensatory tracking error will be differentially affected by increased exponential time-lag constants resulting in a U-shaped curve. This experimental hypothesis follows Helson's U-hypothesis for human performance (14).

2. Compensatory tracking error will be significantly increased with increased magnitudes of front-to-back transverse accelerations. The locus of acceleration and error points will describe a positively accelerated function.

3. Compensatory tracking error at each of various acceleration levels will follow a U-shaped curve when plotted as a function of exponential time-lag constants. This follows Helson's Principle of Generality (14).

II. METHOD

A. Apparatus

The apparatus consisted of elements: (1) a human centrifuge, (2) analog computer, (3) curve followers, (4) oscilloscope display, (5) control system, and (6) recorder. Each of these elements are discussed below:

1. Human Centrifuge. The acceleration environment was produced on the human centrifuge located at the University of Southern California. The subject was seated on one arm of the superstructure, which is fifty feet in diameter, facing the center of rotation. In this way, front-to-back transverse accelerations (force direction through the chest, perpendicular to the blood column) in the order of 3.0g and 6.0g were produced. The subject was seated in a typical aircraft ejection seat at an effective radius of 15.5 feet. Figure 1 shows a subject seated in the human centrifuge.

FIG 1 THE SUBJECT SEATED IN POSITION TO EXPERIENCE FRONT-TO-BACK ACCELERATION ON THE HUMAN CENTRIFUGE. NOTE THE RELATIVE POSITIONS OF THE SUBJECT, OSCILLOSCOPE AND RIGHT HAND CONTROLLER.

2. <u>Analog Computer</u>. An analog computer was used for the purpose of simulating the aircraft control environment. It was the original design and property of North American Aviation, Inc. Exponential time-lag constants of 0.1, 1.0, and 2.0 seconds were produced by means of the analog computer to test the experimental hypotheses. These values were selected to be in agreement with values used in other studies and, also, because they bracket extremes of high performance aircraft aerodynamic response characteristics.

3. <u>Curve-followers</u>. Two curve-followers were used for presenting the task to the subject, one for the pitch mode, the other for the roll mode. Each task mode was a complex wave form suggested by representatives of North American Aviation, Inc., as approximating a high performance aircraft in turbulent conditions. The time duration of the task was made to be sixty seconds so that it would be in agreement with other studies of this nature and also to require the subject to be exposed to the accelerative environment for a suitable amount of time. Figure 2 shows the curve-followers, in association with the analog computer, in the recorder room.

FIG 2 THE CURVE-FOLLOWERS AND THE ANALOG COMPUTER IN THE CONTROL ROOM.

4. Oscilloscope display. The complex wave forms noted above were used to disturb a horizontal line on the center of the oscilloscope face. The line represented the subject's own aircraft and was programmed to move vertically to indicate pitch and rotate about its center to indicate roll. The subject was required to hold the aircraft representation at zero degrees in pitch and roll angles, any deviation from the horizontal-center position representing a tracking error. Two markers were placed on the oscilloscope face in order to denote the center as an additional cue for the subject. Figure 3 shows the aircraft representation in a position depicting a large error in the roll mode. In this case the subject would have to make a roll motion to the right to correct for this error.

FIG 3

THE AIRCRAFT REPRESENTATION ON THE OSCILLOSCOPE SHOWING A ROLL ERROR BUT NO PITCH ERROR.

5. Control system. The control stick used in this program was the prototype X-15 right hand controller. It was designed so that the pilots' wrist (ulnar styloid) was the pivot point for both pitch and roll modes. Before data runs were begun, the stick was "mass balanced" so that it would not be displaced by the accelerative force, thereby inducing errors which would not be attributable to the voluntary control motions of the subject. An adjustable armrest

was provided so that each subject could position himself comfortably in relation to the control column. The armrest was adjustable vertically and longitudinally.

6. Recorder. The recorder used in this study was an eight channel Offner Dynograph. Four channels of information were used for each of pitch and roll measurements, as follows: (a) task input (stimulus), (b) stick input (response), (c) absolute error (the difference between (a) and (b)), and (d) the integration of the absolute error. The integrated error in volts, for each mode, is used as the dependent variable for this study. Figure 4 presents a typical record showing each of the eight channels.

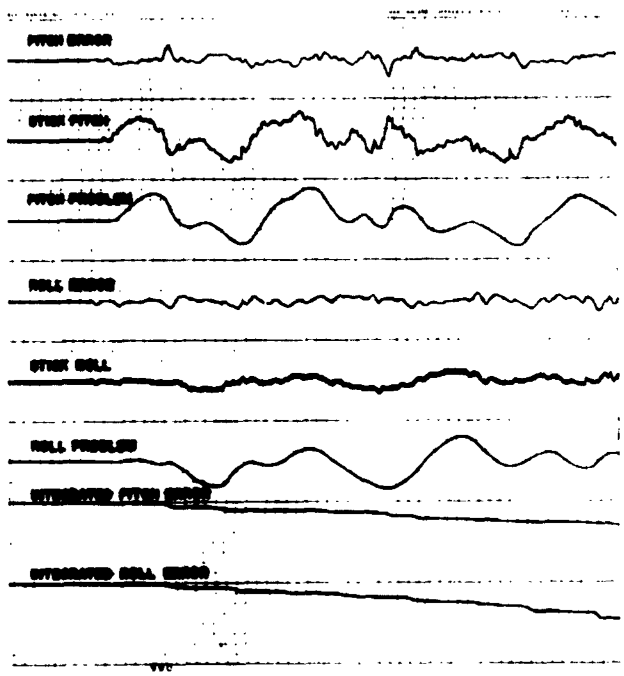

FIG 4 A TYPICAL RECORD SHOWING THE USE OF EIGHT CHANNELS FOR DATA RECORDING AND REDUCTION.

B. Subject Group

Thirty-five male students at The University of Southern California served as subjects for this investigation. They ranged in age from twenty-one to twenty-six. The vast majority of the subjects were members of the Naval Reserve Officers Training Corps on the campus. As such, they were a group of subjects who might be expected to become Naval Aviators within the next two years. Moreover, the mental and physical requirements for acceptance to the N.R.O.T.C. program is evidence for the high caliber of the subject group., The remainder of the subject group were individuals who had been subjects for other experiments and possessed the same high qualities of the N.R.O.T.C. group.

Each prospective subject was asked to visit the centrifuge facility where a staff member discussed the purpose of the program and gave a general orientation on the operation of the centrifuge. If the individual desired to participate, and was medically approved, his name was added to a selection list. From this list, thirty-six subjects were randomly selected and assigned to one of three groups, one for each time-lag constant. This selection was made by use of a Table of Random Numbers. One subject subsequently dropped from the program, leaving eleven subjects in the 2.0 time-lag group. Since the experimental design did not require equal numbers in the experimental groups, he was not replaced. All subjects were paid for their services as a motivating agent.

C. Procedure and Experimental Design

The experiment was designed so that the data could be subject to statistical treatment by the analysis of variance method. The specific design was a Linquist (21) "Type I Mixed" design.

In many factorial experiments the number of treatment-combinations is so large that it is not practicable to administer all of them to each subject. Lindquist (21) points out that it is possible to set-up a design in which each subject takes more than one but not all of the combinations so that some of the treatment comparisons are inter-subject and some are intra-subject. This, by definition, is a "mixed" design. This "mixed" design was chosen, rather than a complete factorial design, in view of the high costs in time and money to process each subject on the centrifuge and the analog computer.

The "Type I" design is a two factor (A X B) design in which each of the "A" treatments in combination with any one "B" treatment is administered to the same subject, but with each "B" treatment administered to a different group of subjects.

In the present case, the "A" treatment was the front-to-back acceleration levels of (1) static (0 g in the transverse direction), (2) 3.0 g and (3) 6.0 g. The "B" treatments were exponential time-lag constants of (1) 0.1, (2) 1.0 and (3) 2.0 seconds. As was noted earlier, the subjects were randomly assigned to one of the time-lag groups ("B" treatments). All subjects, therefore, received all of the acceleration ("A") treatments but performed the tracking task with only the one assigned time-lag constant. The intra-subject comparison was, therefore, between acceleration treatments, and the inter-subject comparison, between time-lag constants.

Each subject was given twenty static, four 3.0 g and four 6.0 g trials over a two-day period. On the first day, the subjects received ten static trials in two blocks of five each. Each trial was separated by a one-minute rest period, and the blocks, by a three-minute rest period. The rest periods were provided to reduce fatigue effects. After the last static trial, the subjects were exposed to acceleration levels in the following magnitudes and order: 3.0 g, 6.0 g, 3.0 g, 6.0 g. There was a minimum rest period of three minutes between the centrifuge exposures.

On the second day, the subjects received the same order up to and including the first exposure to 3.0 g and 6.0 g. Each time-lag group was randomly dichotomized; one-half receiving the final 3.0 g run prior to the 6.0 g, and the other half received the final 6.0 g run prior to the 3.0 g run. This was accomplished to counterbalance possible fatigue and practice effects.

The measurements used for data evaluation in the analysis of variance were the last static, 3.0 g, and 6.0 g runs on the second day. A static run was not used to counterbalance the dynamic runs as noted above, since the line on the oscilloscope "drifted" as a function of acceleration and required a significant time delay waiting for the scope line to return to the normal position. The error due to "scope drift" was determined experimentally and was subsequently "integrated out" of the final error measurements.

III. RESULTS AND DISCUSSION

A. Pitch Mode

Figure 5 presents the mean pitch integrated error values as a function of the number and type of practice trials. A visual inspection of the figure indicates the following results:

1. The error scores and their relative position are stable by the end of the static trials on the second day. This amount of practice before stabilization is in agreement with results on similar tracking tasks reported by Gordon (12), Gagne and Foster (10) and others.

2. There are relative large differences from the first to the second of each acceleration level on the first day. This is not true, however, for measures on the second day, indicating that the data are becoming asymptotic and that learning, at least in the relative sense, is minimized.

3. The 0.1 second lag consistently produces higher error scores for static and accelerative conditions.

4. There is a sizeable difference in the rate of learning between the 1.0 and 2.0 seconds lags in the early practice trials.

5. There is a definite reversal in the relative order after the sixth trial on the second day. Prior to this time, a U-function was indicated, in that the 1.0 second time-lag constant produced the least amount of error, as predicted. Later in the practice series, however, the 2.0 seconds lag reverses position with the 1.0 second lag.

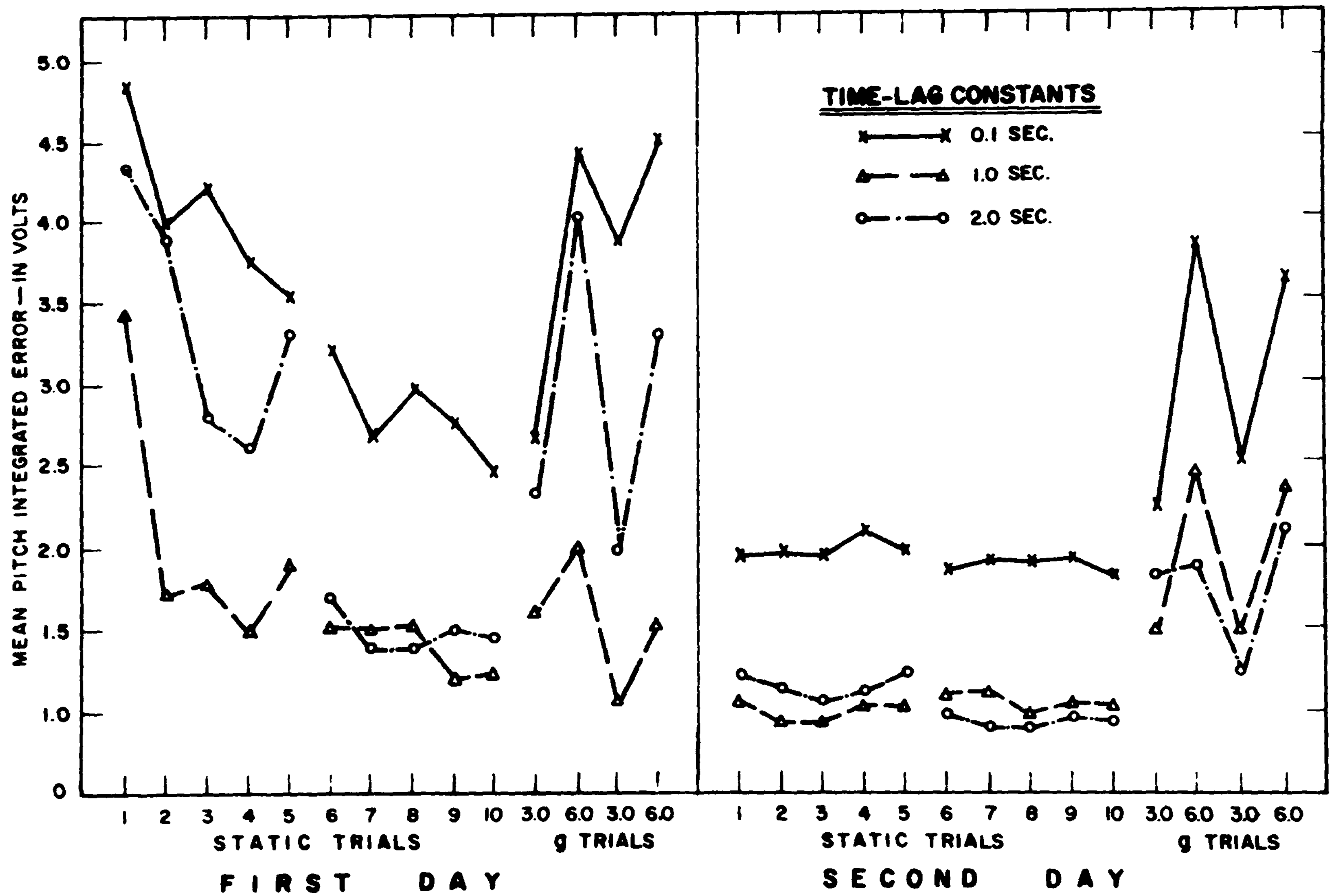

FIG 5 MEAN PITCH INTEGRATED ERROR VALUES AS A FUNCTION OF PRACTICE TRIALS CONDUCTED OVER A TWO DAY PERIOD.

A feasible explanation for the reversal noted above is in terms of the information-learning aspects. In particular, McGeoch and Irion (24) concluded that for most efficient learning, knowledge of results should be administered as quickly and as specifically as possible. When items 4 and 5, above, are considered together, it is apparent that since the 2.0 second lag provides less feedback of information, or reinforcement, the learning will take place at a slower rate and, hence, require a longer period of time for the performance score to reach an asymptote.

Although this learning phenomenon has essentially "destroyed" the predicted pitch U-function, it serves as an excellent example of the problems of doing research with human subjects. First, the problematic, ever-present adaptability of the human, as was noted earlier at great length, makes prediction a very difficult task. Secondly, researchers in the area of human performance should be critical of learning phenomena so that they avoid the pitfall of making conclusions before they are certain that complete adaptation or a limit has been reached.

Table 1 presents the mean pitch integrated error for the last static, 3.0 g and 6.0 g trials. Figure 6 presents these results graphically and, as predicted, the acceleration data produces a consistent family of curves. The U-function, of course, was not obtained although the resultant curve might be described as a "half" U-function. Presenting the results in another way, Figure 7 indicates that increased acceleration increases mean pitch error.

TABLE 1

MEAN PITCH INTEGRATED ERROR, IN VOLTS, OBTAINED FOR THE VARIOUS ACCELERATION LEVELS AND TIME-LAG CONSTANTS

Acceleration Levels	TIME-LAG CONSTANTS		
	0.1 Sec.	1.0 Sec.	2.0 Sec.
Static	1.83	1.06	0.95
3.0 g	2.47	1.40	1.32
6.0 g	3.55	2.36	2.15

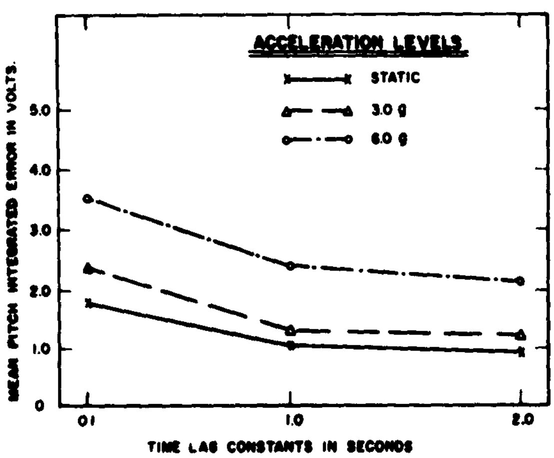

FIG 6

MEAN PITCH INTEGRATED ERROR AS A FUNCTION OF VARIOUS TIME-LAG CONSTANTS AND ACCELERATION LEVELS

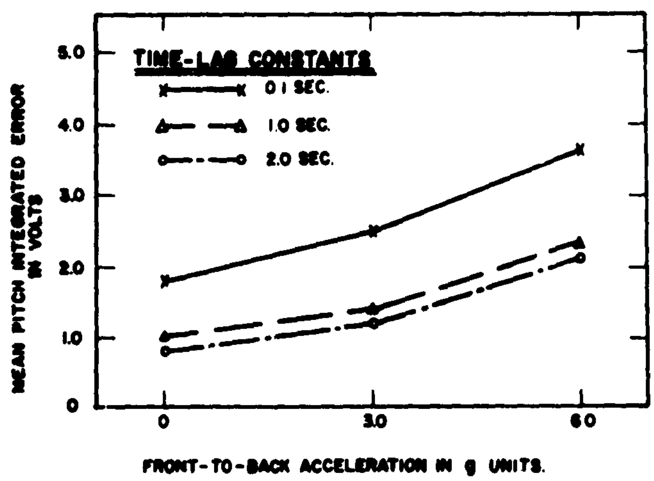

FIG 7

MEAN PITCH INTEGRATED ERROR AS A FUNCTION OF INCREASED ACCELERATION AND VARIOUS TIME-LAG CONSTANTS

Table 2 presents the results of the analysis of variance of pitch error scores. Statistically significant F-ratios were found for time-lag constants, acceleration, and interaction at the .025, .005 and .001 significance levels, respectively.

Two groups of t-ratios were calculated for the various combinations of acceleration levels and time-lag constants in the pitch mode. In the first group, the t-ratios between means for acceleration levels, for each of the time-lag constants, showed statistically significant increases for 3.0 g and 6.0 g. These were significant at the .01 level. These findings support the experimental hypothesis that the measures obtained at 3.0 g would be significantly larger than those obtained statistically and that measures obtained at 6.0 g would be significantly larger than those obtained at 3.0 g.

TABLE 2

ANALYSIS OF VARIANCE RESULTS FOR PITCH ERROR SCORES

Source of Variation	df	MS	F
Between Subjects	34		
Time-Lags (L)	2	12.27	6.93**
Error (b)	32	1.77	
Within Subjects	70		
Acceleration (A)	2	18.29	15.37***
A X L	4	4.03	3.39*
Error (w)	64	1.19	
Total	104		

*p = .025; **p = .005; ***p = .001; Lindquist (21).

In the second group, the t-ratios between means of the time-lag constants at each of the acceleration levels showed that all but the 1.0 and 2.0 second lags at 3.0 g and again at 6.0 g were found to be significantly different. Since the mean error for the 0.1 second lag was significantly larger than the 1.0 and 2.0 seconds lags, and they in turn, were not significantly different from one another, this would appear to be the explanation of the statistically significant interaction F-ratio. In simpler terms, the most difficult task (0.1 second) without acceleration is affected most by increased acceleration. This result meets with prediction by the Principle of Generality.

Table 3 presents the results of computing product-moment correlation coefficients for pitch measurements. It was found that the 3.0 g-6.0 g comparison for all time-lags produced statistically significant coefficients, whereas, no other combination was statistically significant.

TABLE 3

PRODUCT-MOMENT CORRELATION COEFFICIENTS FOR PITCH MEASUREMENTS OBTAINED FOR THE VARIOUS COMBINATIONS OF EXPERIMENTAL CONDITIONS AND TIME-LAG CONSTANTS

Time-Lag Constants	Acceleration Levels		
	Static-3.0 g	3.0 g-6.0 g	Static-6.0 g
0.1	.237	.909**	.115
1.0	.137	.984**	.336
2.0	.408	.619*	-.039

* < .05, ** < .01

One implication from these results for engineering psychologists is that one cannot reliably predict human performance measures under dynamic conditions from static measures. However, it is also indicated that a small amount of stress is sufficient to reliably predict behavior at higher levels. This result questions the validity of ground-based flight simulators as a method for optimizing control systems for vehicles which may encounter a hostile environment during its mission.

B. Roll Mode

Figure 8 presents the mean roll integrated error values as a function of the number and type of practice trials. It may be noted, by visual inspection, that:

1. The error scores are relatively stable by the end of the static trials on the second day.

2. The 2.0 second lag, in the first five trials, produces the greatest amount of error. By the static trials on the second day, it definitely moves between the 0.1 and 1.0 second lags.

3. The 1.0 second lag generally produces the least amount of error, although there are a small number of reversals.

The roll data, from the first trial on, definitely show a U-function. As practice continues, the 2.0 seconds lag reverses position with (produces less error than) the 0.1 second lag. This reversal does not, however, change the U-shape since the 1.0 second lag is always optimum. The information-learning explanation for the 2.0 second lag reversal in pitch would appear to satisfy the present reversal.

Table 4 presents the mean roll integrated error for the last static, 3.0 g and 6.0 g trials. Figure 9 presents these results in graphic form and, as was found with

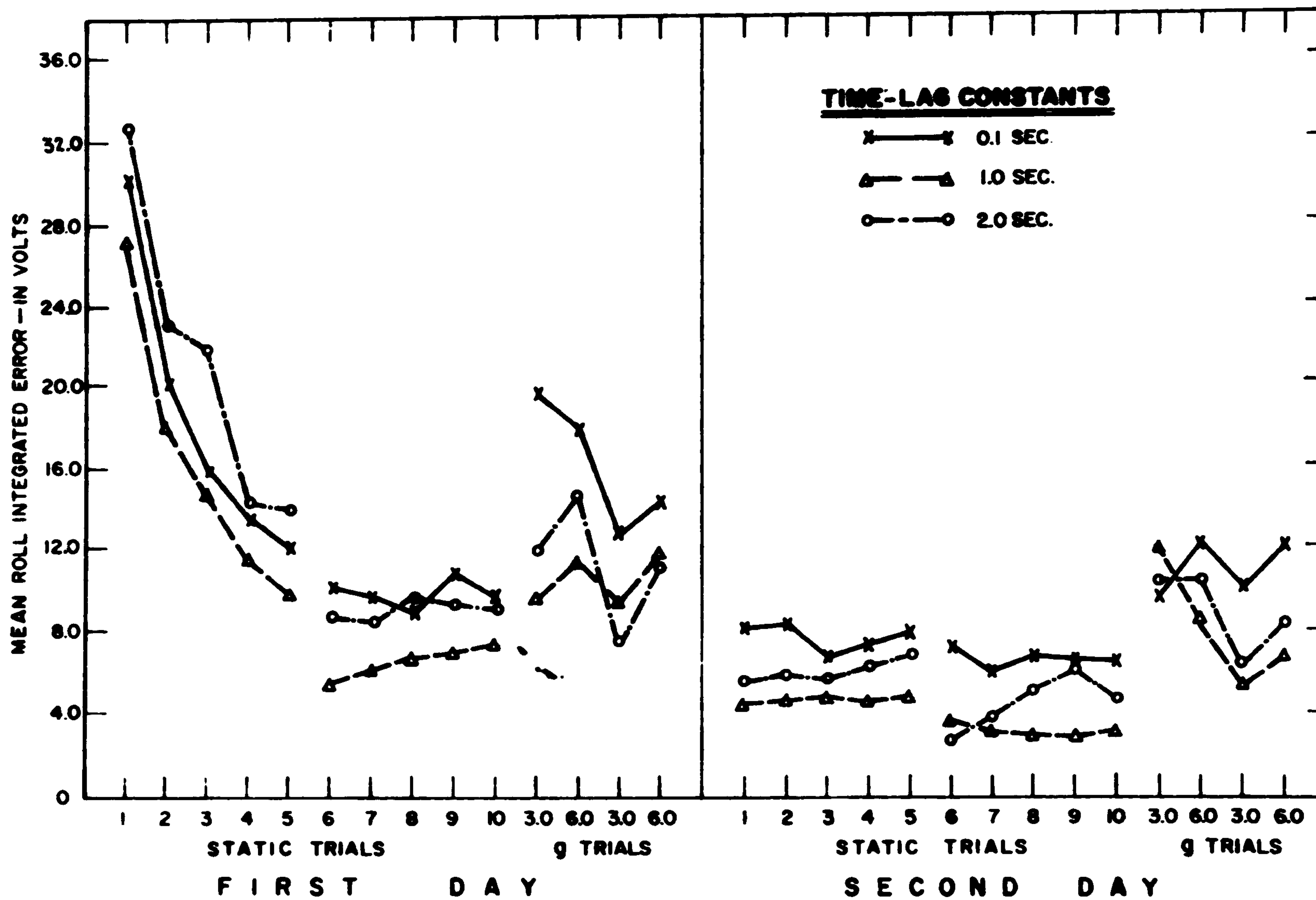

FIG 8 MEAN ROLL INTEGRATED ERROR VALUES AS A FUNCTION OF PRACTICE TRIALS CONDUCTED OVER A TWO DAY PERIOD

TABLE 4

MEAN ROLL INTEGRATED ERROR, IN VOLTS, OBTAINED FOR THE VARIOUS ACCELERATION LEVELS AND TIME-LAG CONSTANTS

Acceleration Levels	TIME-LAG CONSTANTS		
	0.1 Sec.	1.0 Sec.	2.0 Sec.
Static	5.29	3.76	5.21
3.0 g	9.75	4.48	5.49
6.0 g	11.95	7.80	8.28

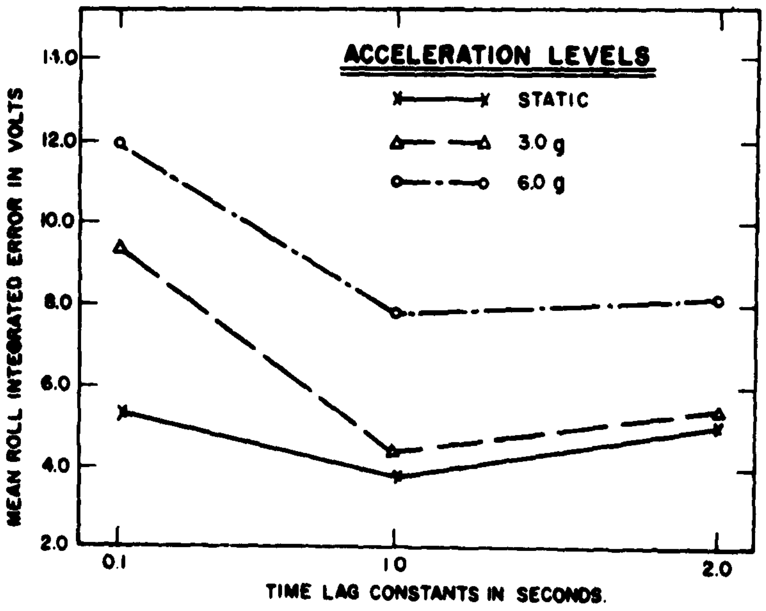

FIG 9 MEAN ROLL INTEGRATED ERROR AS A FUNCTION OF VARIOUS TIME LAG CONSTANTS AND ACCELERATION LEVELS

pitch, acceleration data form a consistent family of curves. Moreover, a rough U-function was found, as was predicted. Figure 10 shows the increase of mean roll error as a function of each level of increased acceleration.

Table 5 presents the results of the analysis of variance of roll error measurements. Statistically significant F-ratios were found for time-lags, acceleration and their interaction at the .001, .025 and .05 significance levels, respectively.

Two groups of t-ratios were calculated for the combination of acceleration levels and time-lag constants in the roll mode. In the first group, the t-ratios between means for acceleration levels, for each of the time-lag constants, showed statistically significant increases for 3.0 g and 6.0 g at the .01 significance level. This is the same result as was shown for the pitch measurements and, again, supports the hypothesis that increased acceleration significantly increases error scores.

In the second group, the t-ratios between the time-lag constants at each acceleration level indicated that the error produced by use of the 0.1 second lag at 3.0 g and 6.0 g is significantly larger than that produced by the other two lags. There was no statistically significant difference between the 1.0 and 2.0 second lag in this case.

It is interesting to note, however, that a "true" U-function is found under static conditions. This was demonstrated by the result that the 0.1 second lag is significantly larger than the 1.0 lag, and the 2.0 second lag is significantly larger than the 0.1 lag, but the 0.1 and 2.0 lags are not significantly different. Increasing the acceleration level, however, distorts this relationship.

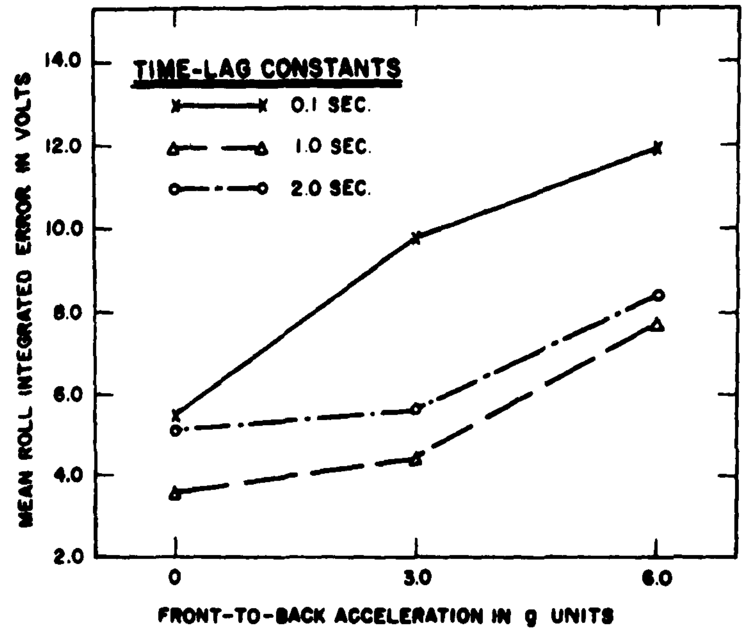

FIG 10 MEAN ROLL INTEGRATED ERROR AS A FUNCTION OF INCREASED ACCELERATION AND VARIOUS TIME-LAG CONSTANTS

TABLE 5

ANALYSIS OF VARIANCE RESULTS FOR ROLL ERROR SCORES

Source of Variation	df	MS	F
Between Subjects	34		
Time-Lags (L)	2	128.09	9.26*
Error (b)	32	14.09	
Within Subjects	70		
Acceleration (A)	2	190.10	19.14*
A X L	4	58.87	5.93*
Error (w)	64	9.93	
Total	104		

*p = .001; Lindquist (21).

Table 6 presents the results of computing the product-moment correlation coefficients for roll measurements. If was found that all but one are statistically significant. This is contrary to what was found for pitch, in that for roll measurement, accurate predictions of performance under acceleration can be made from measurements obtained from static conditions.

C. Some Interpretations of the Results

From the analysis of the results, it appears that all three experimental hypotheses were demonstrated in this study. However, several interesting relationships occurred which bear further discussion.

The reversals in the learning curves for the 2.0 seconds time-lag constant, in both pitch and roll modes, were attributed to an information-learning situation in light of well defined classical notions. In so far as the data are consistent, one might conclude that the information theory approach is one solution for skilled motor theory construction. If this were the case, how does one obtain a U-function? Information theory does explain the "right hand" side of the U, but what about the "left hand" side?

In looking at this study from an informational point of view, the subject is receiving considerably more feedback information per unit time with the 0.1 second time-lag constant than that with the 1.0 second time-lag. Why, then, should more error be accrued with the greater information feedback?

It may be noted that Hunt (17) found that performance improved in a negatively accelerated fashion as the amount of information increased. It may be inferred from a

TABLE 6

PRODUCT-MOMENT CORRELATION COEFFICIENTS FOR ROLL MEASUREMENTS OBTAINED FOR THE VARIOUS COMBINATIONS OF EXPERIMENTAL CONDITIONS AND TIME-LAG CONSTANTS

Time-Lag Constants	Acceleration Comparisons		
	Static-3.0 g	3.0 g-6.0 g	Static-6.0 g
0.1	.642*	.971**	.484
1.0	.663**	.981**	.911**
2.0	.907**	.899**	.736**

* $< .02$, ** $< .01$

negatively accelerated curve that performance will reach a limit or maximum value, even though it may later decline rather than become asymptotic.

McCormick (23), in a machine analogy, points out that any given communication channel has a limit or capacity. In investigations of the human as a communication system, Mackworth and Mackworth (22) conclude that each sense modality has a capacity in terms of the information load and speed which it can handle. Load, according to these authors, as applied to the input through the senses, refers to the variety of stimuli to which differential responses must be made. Thus, if the operator must discriminate among several different classes of visual stimuli, the load on the visual system is greater than if the discrimination is of only one type. Speed, on the other hand, relates to the number of stimuli per unit time. It may be noted that the pitch and roll modes may be considered the load, and the lags the speed, in the present study.

McCormick (23) indicates, based on the results of a number of experimental evaluations, that speed and load are somewhat independent task variables. While performance for any load is affected by speed, there are distinct differences in performance for varying loads. A general statement is that the greater the number of sources of information to which responses are made, the poorer the total performance.

Fitts (9) and Hick (15) have reported classical work in this area. Based on many experiments, they agree that the performance capacity of the human motor system, together with its associated visual and proprioceptive feedback mechanisms, when measured in information units, is constant. Fitts (9) reports the optimum level to be between 10 and 12 bits per second, whereas, Hick (15) reports it to be in the order of 5 bits per second. These numerical differences are not limiting to the general validity of information theory, but rather, Allusi, et al., (1) reports that it is the combinations of stimuli and responses (S-R interactions) that determines the performance level attained. The differences noted above are no doubt due to the conditions of the various experiments.

It is now evident that there is a limiting condition which can be accounted for by information theory. Ely, Bowen, and Orlansky (7) state that man is in a "psychological refractory period" while decisions are being processed, and Fitts (9) reports that "the fixed information-handling capacity of the motor system probably reflects a fixed capacity of central mechanisms for monitoring the results of the ongoing motor activity while at the same time maintaining the necessary degree of organization with respect to the magnitude and timing of successive movements."

It is apparent that the above situation existed in the present study and accounted for the half and full U-functions obtained for pitch and roll, respectively. It may be recalled that Rockway (27) reported that the addition of a lag would serve to reduce the output amplitude if the gain were too high and caused continual overshooting. A high gain, therefore, would probably interfere with the "psychological refractory period". Comments by the operating crew, several experimental test pilots and other visitors, who had the opportunity to track with all three time-lag constants, unanimously reported that the addition of a lag made the task "easier" and also required less control motions. Visual inspection of the data supports this latter statement. One of the test pilots said that "tracking with the 0.1 second lag was like flying an F-100 in a rain storm". This, he reported, was not true with the increased time-lags.

There are several implications that should be put to test from the above discussion: (1) pitch and roll tasks should be conducted separately, following the "load" principle, to determine optimum points singly, (2) pitch and roll measures should be obtained together with all of the combinations of time-lags, for example, the 0.1 second lag in pitch should be combined with the 1.0 and 2.0 seconds lag in roll, etc., to determine their interrelationships, (3) electromyographic, and time and motion studies should be conducted to determine energy and muscle potential changes with increased exponential lags, (4) a systematic evaluation of the stimulus gain properties should be made to determine the inflection point from a linear (consistent degradation of performance) error function to a U-function.

Another interesting occurrence is the consistent interaction of the acceleration levels with the 0.1 second lag. This would appear to be due to the increased muscular requirements, as was noted by visual inspection of the data and subjective report, for the 0.1 second lag as compared with the other lags.

Holland (16) has suggested the neuromuscular lag-time be kept to a minimum since it is one of the prime causes of falling short of the "one-to-one correspondence". This was supported by tracking results of Faber (8) and

Wilkie (29). Analyses of movement times under various types and levels of acceleration, (Bryan (4), Kaehler and Meehan (19) and others) attribute increased motion times to increased muscular load as a function of the magnitude and direction of the accelerative force.

It becomes evident that the reported interaction is due to increased neuromuscular response times caused by the requirement for more muscle activity and, hence, is more prone to be affected by increased acceleration.

A final observation is that of the differential results of the correlation coefficients for the pitch and roll mode. It may be recalled that statistically significant coefficients in pitch were found only for the 3.0 g-6.0 g comparison. In the roll mode, however, all but one were statistically significant. It may also be recalled that Bryan (4) and Kaehler and Meehan (19) reported a differential effect of the direction of the accelerative force on the time to make certain movements. In essence, it was found that motions perpendicular to the direction of the force was less affected than those in the same direction. This fact is important in that the pitch motions are in the direction of the accelerative force under front-to-back acceleration, whereas, the roll motions are perpendicular to it.

The pitch correlation coefficients indicate that some amount of the accelerative condition is necessary to make reliable predictions. This might be a relatively important consideration for the users of static simulators since their present goal is to predict human control performance from static conditions to space missions where hostile environments are to be encountered. Since the roll coefficients were not so affected, the differential principle is indicated as the probable reason.

IV. SUMMARY AND CONCLUSIONS

A. Summary

A study was conducted to determine the effects and interactions of increased front-to-back transverse accelerations and various exponential time-lag constants on human performance.

Thirty-five male undergraduate students served as subjects for this investigation. A "mixed" statistical design was used so that each subject would track with only one value of exponential time-lag in the control system, but would be exposed to all of the acceleration conditions. For the purposes of this study, exponential time-lag constants of 0.1, 1.0 and 2.0 seconds were chosen since they bracket the aerodynamic response characteristics of high performance aircraft. Measurements were obtained under acceleration conditions of static or zero transverse g, 3.0 g and 6.0 g. The maximum g value is that predicted for manned space vehicle boost conditions.

The tracking task consisted of a horizontal line on the face of a cathode ray oscilloscope which moved vertically to indicate pitch and rotated about its center to indicate roll. This was a two dimensional compensatory problem requiring the subject to hold the display at zero degrees in pitch and roll angle. Any deviation from the horizontal-center position would indicate a tracking error. The stimulus, in each mode, was a complex wave form representative of an aircraft flying in turbulent conditions, with a duration of 60 seconds. The control stick was a right-hand side controller designed so that the pilot's

wrist is the pivot point for both pitch and roll. Exponential time-lag constants were produced by use of an analog computer. The measurement of tracking performance was the integration of the absolute error in both control modes. The subjects were given twenty static practice trials and eight centrifuge trials. The data used for the statistical evaluation were the last static, 3.0 g and 6.0 g measurement for each subject. Accelerations were produced on the University of Southern California Human Centrifuge. Analysis of the data was accomplished by analysis of variance, t-ratio and correlation statistical methods.

B. <u>Conclusions</u>

Within the limits of this experiment, a number of conclusions are presented.

1. In general, the experimental hypotheses were supported by the results obtained.

2. Only the first half of a U-function was found for the pitch mode. During the early practice trials, however, there was a definite U-function with the 1.0 second time-lag being optimal. Subsequently there was a reversal making the 2.0 seconds time-lag optimal. This finding does not, however, reject the U-function. It may be noted that the error is decreased as time-lag is increased, which is the major issue of the U-function.

3. A definite U-function was found in the roll mode. Measurements obtained at the static level showed the 1.0 second time-lag to accrue significantly less error than

the other two.

4. Increased magnitudes of acceleration significantly increased error scores in both control modes.

5. Consistent families of curves were produced which support predictions from the Principle of Generality.

6. Helson's U-Hypothesis and Principle of Generality were substantiated and proved to be extremely useful for prediction.

7. Coefficients of correlation between acceleration level measurements indicated that, for the pitch mode, a small amount of acceleration was required to predict performance at higher levels. For the roll mode, the data were sufficiently reliable to make predictions from static measurements. These results support the "differential effect" findings of some researchers and are of practical import in view of the great amount of "control system optimization" activities using static simulators.

8. The use of concepts from information theory appear to explain certain of the learning phenomena occuring in the experiment and, critically, offered an explanation on why a U-function may be achieved under certain stimulus-response conditions.

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